# Measuring atomic oscillator strengths by single atom spectroscopy


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We propose a method for assessing the oscillator strengths of atomic transitions based on single atom spectroscopy. The method is based on a direct measurement of an AC Stark shift of atomic energy levels for the single atom trapped in an optical tweezer. The method is independent on a knowledge of the trapping field at the atom. The results can be applied to obtaining the previously unknown oscillator strengths for dipole transitions involving the first excited state of alkali metals.


## Theory

For a wide variety of laser cooling and trapping experiments, the atoms are trapped in optical dipole traps formed by far-off resonant laser fields (FORT). Consequently, the atomic level structures experience an AC Stark Shift, which for a state $|F, m_F\rangle$ in a FORT of frequency $\omega$ is given by:

$$\Delta E(F, m_F) \approx \sum_{F', m_{F'}} \left\{ \frac{|\langle F, m_F|V_-(\vec{r})|F', m_{F'}\rangle|^2}{\hbar(\omega_F - \omega_{F'} + \omega)} + \frac{|\langle F, m_F|V_+(\vec{r})|F', m_{F'}\rangle|^2}{\hbar(\omega_F - \omega_{F'} - \omega)} \right\},$$

where $\hbar\omega_{F,F'}$ refer to the energies of the unperturbed states and the summation is carried over all the states coupled to $|F, m_F\rangle$. $V_\pm(\vec{r})$ characterise the polarisation and intensity of the FORT. Since each $|\langle F, m_F|V_\pm(\vec{r})|F', m_{F'}\rangle|^2$ is related to the oscillator strength of the related transition, we may obtain the values of a given number of unknown oscillator strengths by solving a system of equations obtained from measuring a set of $\Delta E(F, m_F)$, varying $\omega$. $\Delta E(F, m_F)$ can be measured by observing the the absorption frequency of the $|F, m_F\rangle$ to ground state transition with a probe beam that interacts with a trapped single atom in a simple transmission measurement:[1]

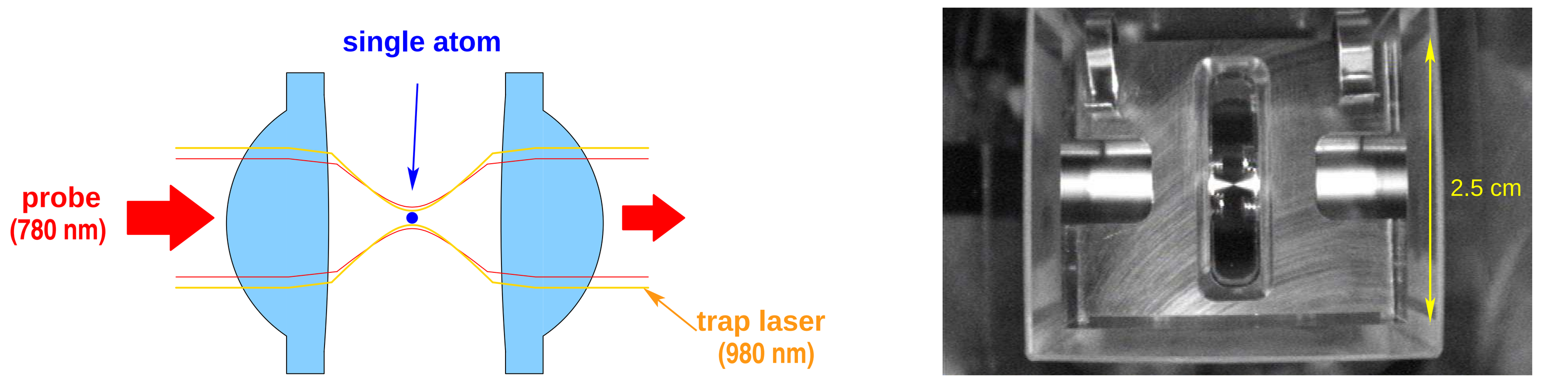


Figure 1: (Left) A probe focused onto a single atom localized by an optical dipole trap. Part of the probe is scattered by the atom, resulting in a drop in transmission. (Right) Photograph of the probe beam passing through the lens system. The bright white beam is due to fluorescence of many Rubidium atoms.

In order to achieve maximum extinction, the $^{87}$Rb atom is optically pumped into the $|5S_{\frac{1}{2}}$, F=2, $|m_F|$=2$\rangle$ to $|5P_{\frac{3}{2}}$, F'=3, $|m_{F'}|$=3$\rangle$ transition, using a circularly polarized probe. The 980 nm FORT light is also circularly polarized. The atom in the FORT experiences an AC Stark shift as shown in figure 2, from which $\Delta E(F, m_F)$ of the $|5P_{\frac{3}{2}}$, F'=3, $|m_{F'}| = 3\rangle$ states can be inferred.[i]

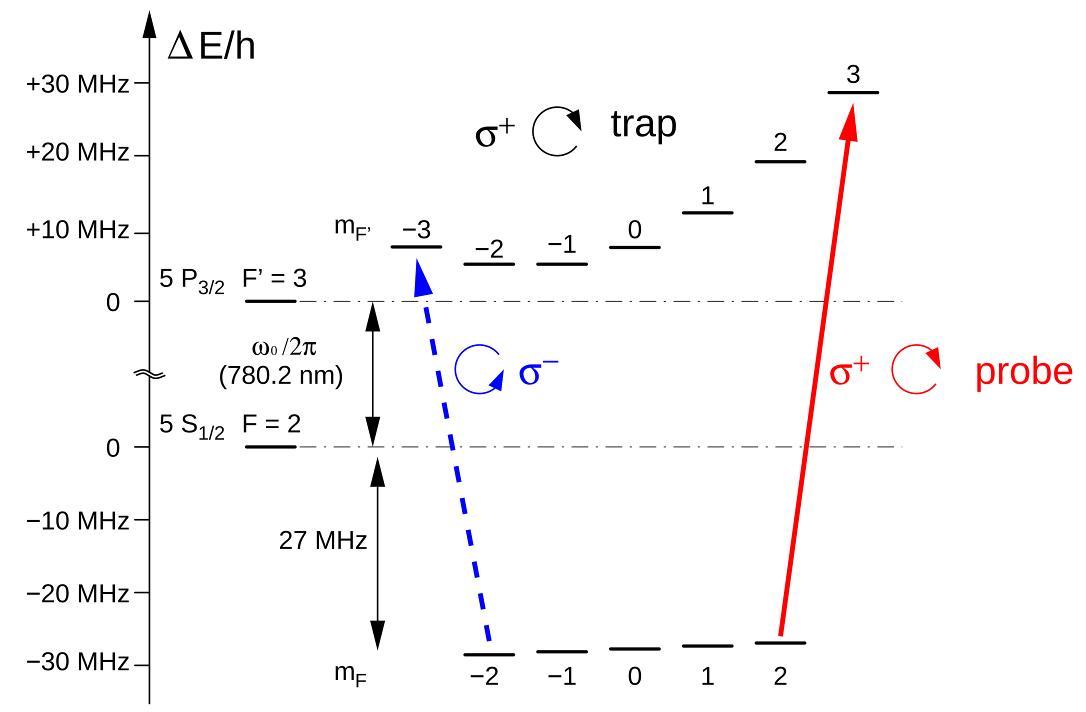


Figure 2: AC Stark shift of $^{87}$Rb atom in the 980 nm circularly polarized FORT, calculated for our experimental parameters.

## Experimental Setup

The heart of our setup consists of two identical aspheric lenses mounted in a confocal arrangement inside an ultra high vacuum chamber. The Gaussian probe beam is delivered from a single mode fiber, focused by the first lens, fully collected by the second lens, and finally coupled again into a single mode fiber connected to a Si-avalanche photodiode. Cold atoms are loaded into the FORT from a magneto optical trap (MOT). The FORT beam has a waist of 1.4 $\mu$m at the focus. Due to the small size of the FORT, a collisional blockade mechanism allows no more than one atom in the trap at any time.[2] The transmission value is defined as the ratio of count rates of detector D1 with to without an atom in the trap.

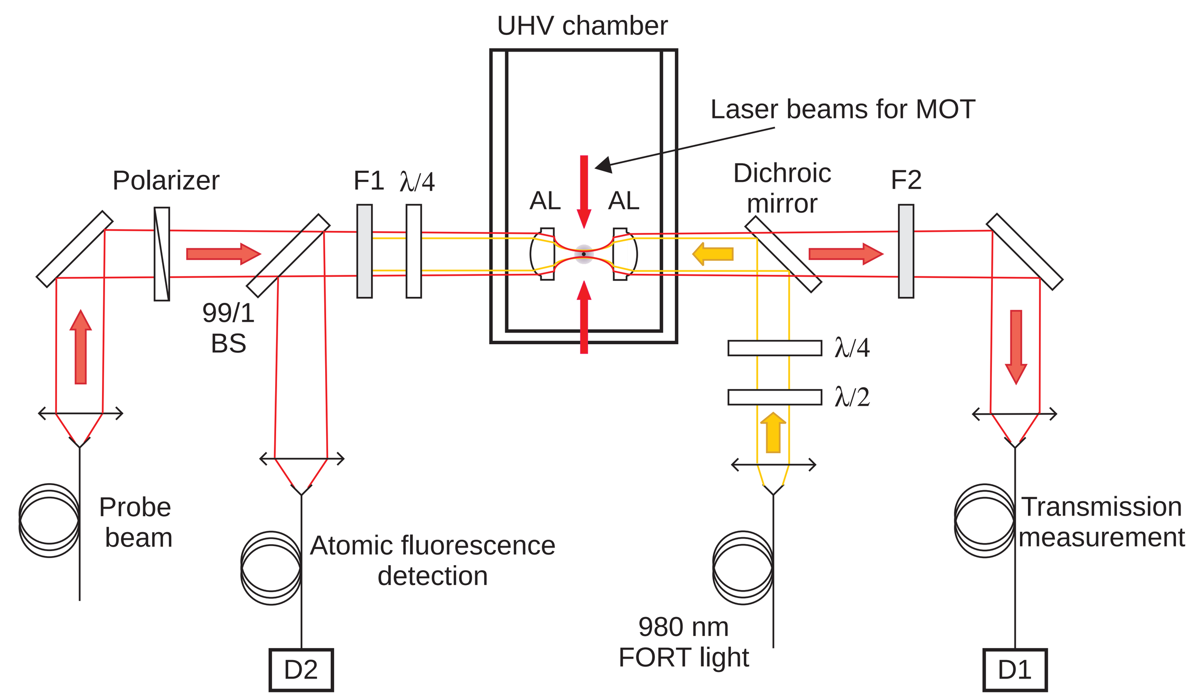


Figure 3: Experimental setup for measuring the extinction of a light beam by a single atom. AL — aspheric lenses (f = 4.5 mm, NA = 0.55), F1 — filter to block 980 nm light, F2 — 780 nm line filter to block 795 nm repump light, D1 and D2 — Si-avalanche photodiodes.

## Transmission Spectra of a Single Atom

Figure 4 shows the transmission spectra a single $^{87}$Rb atom obtained for left-hand and right-hand circularly polarized probes. The horizontal axis shows the probe detuning from the natural resonant frequency of the aforementioned transition (without AC Stark shift). A maximum extinction of $10.4 \pm 0.1$% is measured for this particular setup in which the probe has a focal waist of $\simeq 0.8$ $\mu$m. The $\sigma^-$ probe gives a bigger extinction because optical pumping is more efficient for this polarization[1].

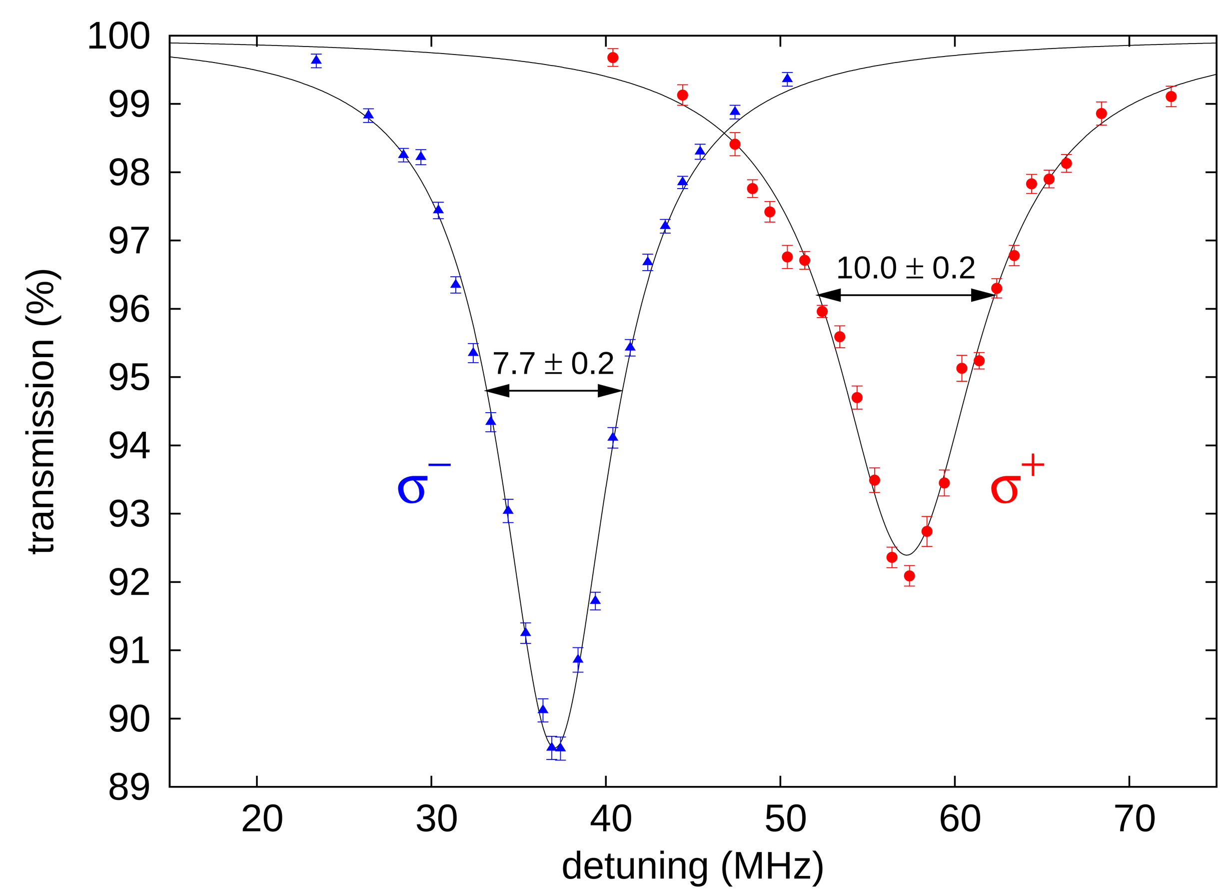


Figure 4: Transmission spectra of a single $^{87}$Rb atom. The full-width-half-maximum of the transmission spectra are comparable to the natural linewidth of the D2 transition in $^{87}$Rb atom (6 MHz).

## Temperature Estimation of Single Atom

Thermal motion of the single atom within the dipole force trap means that it experiences a position-dependent probe intensity approximately:

$$I(\varrho, z) = -I_0 \left[ 1 - 2\left(\frac{\varrho}{\omega_D}\right)^2 - \left(\frac{z}{z_R}\right)^2 \right]$$

under thermal motion in the harmonic trap, the average intensity experienced by the atom is:

$$\langle U \rangle_{T,U_0} = \frac{2^3}{T_x T_y T_x} \int_0^{U_0} dE\, \rho_T(E) \int_{-A_x(E)}^{A_x(E)} \int_{-A_y(E)}^{A_y(E)} \int_{-A_z(E)}^{A_z(E)} \frac{dx dy dz}{v_x v_y v_z} U(x, y, z)$$

since the resonant frequency of the probed transition is directly proportional to $\langle U \rangle_{T,U_0}$, we can extract T.

## Obtaining Oscillator Strengths

The proposal for measuring the oscillator strengths with a single atom in a FORT is as follows

1) Measure the resonant-frequency shifts of the $|F = 2, m_F = 2\rangle$ to $|F = 3, m_F = 3\rangle$ transition ($\Delta f_+$), and of the $|F = 2, m_F = -2\rangle$ to $|F = 3, m_F = -3\rangle$ transition ($\Delta f_-$) for a FORT wavelength. The ratio $r = \Delta f_+/\Delta f_-$ depends only on the known oscillator strengths related to the $5S$ state, and some unknown oscillator strengths related the $5P_{3/2}$ states. As both frequency shifts are directly proportional to the intensity at the focus, the ratio is independent of it.

2) Repeat the previous step $N$ times using FORT of various $\omega$ to get $N$ ratios. Solving the $N$ ratio equations gives the $N$ unknown oscillator strengths. Ideally, the more ratios $r$ are measured, the more accurately one can determine the oscillator strengths.

This proposal assumes that the AC-Stark shift of the atom can be predicted by time-dependent perturbation theory to the second order: i.e. the AC-Stark shifts are small compared to the hyperfine splittings of the atom, otherwise, more sophisticated calculations would be required to correctly predict the oscillator strengths.


References

[1]M. K. Tey et al. Interfacing light and single atom with a lens. *arXiv: 0804.4861v3*

[2] M. K. Tey et al. Strong interaction between light and a single trapped atom without a cavity. *Nature Physics* **4**, 924 (2008)


Footnotes

[i]The AC Stark shift of the $|F = 2, m_F\rangle$ ground states can be theoretically determined as the oscillator strengths involving these states are well documented.